Material Parameter Extraction Using Time-Domain TRL (t-TRL) Measurements

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Abstract—Characterizing materials used in Printed Circuit Board (PCB) manufacturing is becoming increasingly important in link path analysis as the data rates are increasing. The material properties governing the performance of the signal passing through a transmission line are frequency-dependent. Using frequency-domain vector network analyzer (VNA) measurements and Through-Reflect-Line (TRL) calibration, these parameters can be determined accurately. But a Time-Domain Reflectometer (TDR) provides a relatively inexpensive and simple way of characterizing transmission lines, and it is easily accessible to Signal Integrity engineers. With the time-domain TRL (t-TRL) calibration technique [1], it is now possible to de-embed such discontinuities as connectors, cables, etc., in the path of the transmission line using time-domain measurements. From the calibrated results, material properties can be extracted in the same way as it is done in the frequency domain. This paper describes a t-TRL technique to obtain accurate frequency domain S-parameters from time domain measurements. The calibrated results are converted into the ABCD parameters. The propagation constant is obtained through the ABCD parameters, from which attenuation loss and phase constant are extracted. Dielectric constant is extracted from the phase constant and the total attenuation constant. Curve-fitting technique is used to split the losses into conductor and dielectric loss. Once dielectric loss is determined, loss tangent can be calculated. The results are compared for three test vehicles, and are also compared with frequency domain VNA measurements. The results from the t-TRL calibration technique are also compared with another known extraction procedure.

I. INTRODUCTION

This paper describes how the t-TRL calibration procedure [1] can be used for characterizing materials on a printed circuit board (PCB). Several approaches, such as cavity methods and waveguide/transmission techniques, are typically used to characterize materials on a PCB. In order to accurately measure material properties of a PCB, it is important to correctly de-embed the effects of cables, connectors, vias, transitions, etc. In the frequency domain, it is easy to use de-embedding techniques, such as the Through-Reflect-Line (TRL) calibration [2] to eliminate effects of discontinuities at the ports upon measurements. But using a vector network analyzer (VNA) to characterize materials is an expensive and simple way of characterizing transmission lines, and it is easily accessible to Signal Integrity engineers. With the time-domain TRL (t-TRL) calibration technique [1], it is now possible to de-embed such discontinuities as connectors, cables, etc., in the path of the transmission line using time-domain measurements. From the calibrated results, material properties can be extracted in the same way as it is done in the frequency domain. This paper describes a t-TRL technique to obtain accurate frequency domain S-parameters from time domain measurements. The calibrated results are converted into the ABCD parameters. The propagation constant is obtained through the ABCD parameters, from which attenuation loss and phase constant are extracted. Dielectric constant is extracted from the phase constant and the total attenuation constant. Curve-fitting technique is used to split the losses into conductor and dielectric loss. Once dielectric loss is determined, loss tangent can be calculated. The results are compared for three test vehicles, and are also compared with frequency domain VNA measurements. The results from the t-TRL calibration technique are also compared with another known extraction procedure.

II. PROCEDURE OF t-TRL CALIBRATION

The time-domain TRL (t-TRL) calibration [1] technique uses measurement results, converted from the time domain to frequency domain through a complete FFT method [4], [5]. The time drift on TDR/TDT waveforms are corrected using phase rotation in frequency domain. Conventional frequency domain TRL calibration is then applied to those processed measurements. This calibration requires appropriate TRL patterns to be designed on the test vehicle itself.

A. Test Vehicle Design & Dimensions

The design for the test vehicle, proposed in [1], is based on the stripline geometry, where electromagnetic field lines are contained between two planes and the single mode propagating on the line is the TEM mode. The dimensions (in mils), shown in Fig. 1, correspond to approximately 50-Ohm characteristic impedance. TRL test patterns are designed to de-embed the effect of cables, connectors and via transitions [1]. The frequency range is split into four segments so that a pair of THRU/LINE would not be used over the bandwidth of 8:1 ratio. The insertion phase requirements [1] are also taken into consideration. The lengths of the TRL calibration patterns and test traces are shown in Table 1.

![Fig. 1. Dimensions (in mils) of the stripline geometry used for the TVs](image-url)

B. Measurement Procedure

Three test vehicles (TVs) are considered for this experiment. They have the same geometry, stack-up, dimensions and TRL calibration patterns, but types of material...
used for their dielectric differ. They are classified as the high loss (TV1), medium loss (TV2), and low loss (TV3) test vehicle materials. These three types of TVs have been chosen to test how the extraction procedure proposed in this paper works for materials with different dielectric constants and loss tangent values.

Once the test vehicles are populated with flange-mount, compression-fit SMA connectors, measurements can be taken using a Tektronix CSA8200 with an 80E06 TDR Module. This module has a rise time of 11ps with a receiver bandwidth of 50 GHz. The maximum number of points that can be set on the scope is 4000. However, by using the Tektronix’s IConnect software [6], the number of points and the overall time window can be increased. IConnect software stitches several time windows together to form one large time window.

TABLE I

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency Range (GHz)</th>
<th>Length (mils)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>Stop</td>
</tr>
<tr>
<td>THRU</td>
<td>0.05</td>
<td>50</td>
</tr>
<tr>
<td>OPEN</td>
<td>0.05</td>
<td>50</td>
</tr>
<tr>
<td>LINE–1</td>
<td>0.05</td>
<td>0.28</td>
</tr>
<tr>
<td>LINE–2</td>
<td>0.28</td>
<td>1.58</td>
</tr>
<tr>
<td>LINE–3</td>
<td>1.58</td>
<td>8.89</td>
</tr>
<tr>
<td>LINE–4</td>
<td>8.89</td>
<td>50</td>
</tr>
<tr>
<td>TestLine–2</td>
<td>0.05</td>
<td>50</td>
</tr>
</tbody>
</table>

Obtaining a larger time window would increase the frequency-domain resolution. If S-parameters are obtained with insufficient number of points, the phase of transmission parameter would not span the range from exactly $-\pi$ to exactly $+\pi$, and when unwrapping the phase, the slope of the phase constant $\beta$ with respect to frequency would be incorrect. This would significantly impact the accuracy of the extracted values for material properties.

Herein, a total time window of 50 ns has been chosen by setting 5 ns/div. A total of 10,000 points are taken. The waveform is averaged 1,000 times to reduce the noise, associated with the measurements. Once the instrument is set, the following procedure has to be used to measure all the calibration standard loads:

- Time delay on the scope is adjusted so that the incident pulse and the reflected pulse are visible on the screen. The captured incident pulse is used to correct the random time base drift associated with TDR;
- TDR measurement is taken from Port 1;
- TDT measurement is taken from Port 1 to Port 2;
- TDR measurement is taken from Port 2;
- TDT measurement is taken from Port 2 to Port 1.

The above steps are followed for measuring THRU, LINE-1, LINE-2, LINE-3, LINE-4, and TestLine-2, respectively. For the OPEN standard, only the TDR measurements are taken for both ports. Once the waveforms are acquired, they are exported to a data file, which can be used for post-processing.

Fig. 2 shows the TDR waveforms at Port 1 for TV1 after separating the incident pulse from the waveform. Fig. 3 shows the TDR waveforms at Port 2 after separating the incident pulses. The same procedure is repeated to measure TV2 and TV3.

C. Data Processing & Drift Correction

The data file containing the raw measured data is processed. For performing TRL calibration, the measured time-domain data of all the traces has to be converted to frequency domain. One of the major problems associated with time-domain measurement is the time base drift. This is a random phenomenon, which makes the TDR pulse drift along the time axis. This has to be corrected to obtain proper phase information for frequency-domain S-parameters. The time base drift can be corrected in time domain by external shifting of the acquired waveform. In this paper, however, to simplify implementation, the time base drift is corrected using phase rotation in frequency domain.
The first step in processing the data is to manually separate the incident section and the reflected section of the transmission line from the captured waveform as shown in Fig. 2. This reflected section is called the “device under test” (DUT) section. The incident section is used to calculate the phase shift, and the DUT reflected waveform section is used to calculate the S-parameters of the DUT. Fig. 4 and 5 show the TDR and TDT waveforms of the DUT section respectively. The second step is to convert the step-like incident waveform to frequency domain. This is achieved by using a complete FFT technique. This technique uses a combination of Nicolson-ramp and Gans-Nahman methods [4], [5], and has an enhanced frequency resolution, D.C. value, and equally spaced harmonics [1]. The phase shift of each trace with respect to the phase reference of THRU standard is calculated. The third step is to convert the TDT waveform to frequency domain using the complete FFT technique. Raw S-parameters of the different traces are obtained. The fourth step is to rotate phase for each trace with the exact amount of pre-calculated phase shift to compensate for the time base drift. The THRU standard is used as a reference. This procedure allows for converting time domain measurements to phase corrected raw S-parameters for each trace.

D. TRL Calibration

The raw S-parameters obtained from time-domain measurements are saved into touchstone format, and they are used for the TRL calibration. The basic TRL de-embedding procedure [2] can be explained using Fig. 5.

The measured T-matrix for the two-port network can be split into three separate blocks, as shown in Fig. 5. The error boxes can be calculated by measuring the Through-Reflect-Line standards for each frequency range, and the T-matrix of the DUT can be determined. Thus the reference plane is set at the DUT, de-embedding the effect of the cables, connectors and launches as shown in Fig. 5. The T-matrix of the DUT is converted back to S-parameters and saved in touchstone format. This becomes the input to the material extraction program.

E. t-TRL Calibrated Results and Comparison

The calibrated S-parameters obtained from time-domain measurements are compared with the conventional VNA-TRL calibrated results. Fig. 6 shows the transmission loss in dB, and Fig. 7 shows the phase (zoomed view) of transmission loss from 10 GHz to 13 GHz. It can be seen that both magnitude and phase of the t-TRL calibrated S21 agree well with the VNA-TRL calibrated results. However, the magnitude of S21 obtained using t-TRL calibration exhibits high-frequency noise.

![Fig. 4. TDT Waveform at Port 2 after Removing Incident Edge.](image)

![Fig. 5. Two-port TRL Calibration Technique.](image)

![Fig. 6. TRL Calibrated Magnitude of S21 for all the TV’s.](image)

![Fig. 7. TRL Calibrated Phase of S21 for all the TVs](image)
The number of data points in the present study was increased up to 10,000 to get sufficient resolution for a time window of 50 ns, while in [1] the number of points was 4000 or 4096 for a time window of 10ns. As discussed above, this was done to increase the frequency-domain resolution. But the advantage of having a higher resolution is that the phases of S-parameters, obtained in both methods, agree well, since now there are more frequency points to represent phase transitions from \(-\pi\) to \(+\pi\).

The return loss was also compared and correlated with the VNA measurements. The agreement between t-TRL and TRL-VNA calibration results for the return loss has been observed in [1]. The comparison with the VNA measurements was done as a sanity check to verify the t-TRL calibration technique. Now, the touchstone S-parameter file can be used for the material extraction procedure.

III. MATERIAL PARAMETER EXTRACTION

Material properties can be extracted from S-parameters, obtained using the TRL calibration. Since the discontinuities are removed after calibration, the extracted material properties properly portray the behavior of the material. Various efforts have been done to accurately extract the material properties from the measured S-parameters [3], [7]-[9]. Herein, a technique [3], [10] has been adopted for extracting dielectric parameters of PCB substrates.

A. Extraction Procedure

The following approach shown in Fig. 8 is used to extract the frequency dependent material properties, once the calibrated measurement is obtained in the form of touchstone format.

1) S-parameter Sanity Checks: The calibrated S-parameters are checked for obvious problems before doing the material parameter extraction. The S-parameters should be checked for causality using a link-path analyzer [9], and the suspicious points should be removed. Then the reciprocity (the equality of \(S_{11}\) and \(S_{12}\)) is tested. All the transmission lines under the present study are almost perfectly reciprocal. Then the network is checked for symmetry, that is, whether the parameters \(S_{11}\) and \(S_{22}\) are identical. In reality, \(S_{11}\) and \(S_{22}\) may slightly differ due to the inequality of impedances at the ports of the transmission lines. This asymmetry is taken into account in the model as in [3].

2) Material Properties: Once the validity of S-parameter is checked, they are converted to ABCD parameters [2]. Propagation constant is directly related to the ABCD parameters. However, conventional extraction models assume the two ports to be identical. But in reality, \(S_{11}\) is not equal to \(S_{22}\). The corrected expression for complex propagation constant that takes into account network asymmetry is given in [3]. Since exact information on the geometry of the stripline on the manufactured PCB is not always available, an efficient method of separating the two components of loss \((\alpha)\) is the application of curve-fitting using, for example, a simple and robust optimization genetic algorithm (GA) [8].

\[
\gamma = \alpha + j \beta
\]

\[
\alpha = \alpha_c + \alpha_d
\]

\[
\gamma = \alpha = A \sqrt{\omega + B_0}
\]

\[
\alpha_c, \text{ Conductor Loss} \quad \alpha_c = A \sqrt{\omega}
\]

\[
\alpha_d, \text{ Dielectric Loss} \quad \alpha_d = B_0
\]

\[
\epsilon_r = A \sqrt{1 - \frac{B}{A + B}}
\]

\[
\epsilon_r'' = \sqrt{\frac{A^2 \cdot B}{A + B}}
\]

\[
\tan \delta = \frac{\epsilon_r''}{\epsilon_r}
\]

Once dielectric loss and phase constant are obtained as shown in Fig. 8, real and imaginary part of permittivity is calculated [3] using (1) and (2),

\[
\epsilon_r = A \sqrt{1 - \frac{B}{A + B}}.
\]

\[
\epsilon_r'' = \sqrt{\frac{A^2 \cdot B}{A + B}}.
\]

where \(A = \frac{\beta^2 c^2}{\omega^2}\), and \(B = \frac{4 c^2 \alpha_d^2}{\omega^2}\).

This technique assumes that the roughness of the conductor is negligible. But in reality, roughness cannot be neglected for a high speed and low loss material. Improved techniques are being developed to include the effect of surface roughness in the extraction procedure [3], [10], and [11].

B. Results & Discussion

Material properties as functions of frequency can be obtained based on the extraction procedure explained in the previous Section. Fig 9 shows the comparison of dielectric constants for all the three Test Vehicles: TV1, TV2, and TV3. This figure also includes curves extracted from the VNA measurements, and the results obtained using the algorithm developed by [12]. Two transmission lines are required for extracting material properties using this algorithm. The 10-inch test trace was used as the long trace and the THRU standard was used as the short trace. S-parameters from the time-domain measurements were used as the input data for the algorithm in [12].
In the used herein extraction algorithm (Fig. 8), the propagation constant $\beta$ extracted from S-parameters is forced to be linear with frequency in the frequency range of interest (1-15 GHz). This causes Dk to be practically independent of frequency. However, this constant Dk does not reflect the correct nature of permittivity, if the material under test is frequency-dispersive. If Dk is constant, this also causes the Df to be almost constant. Indeed, constant Dk and Df lead to violation of Kramers-Krönig causality relations [3]. However, for the frequency range of interest (1-15 GHz), this is an acceptable approximation, since the materials under study have their Dk and Df deviation less than 5% over the range of interest due to their dispersive nature.

1) Deviation of (t-TRL) TDR vs. VNA: It can be observed in Fig. 9 that the dielectric constant is almost constant over the frequency range. There is a small difference of about 0.5% between the VNA and the TDR results. Even though the time window was chosen to be as large as 50ns, the frequency domain resolution is not high enough to obtain a perfectly correct phase. Hence the slopes of the phase obtained from the two methods were slightly different, causing small deviation in the extracted results.

The mean values of dielectric constant and loss tangent obtained from various test vehicles and by different methods are summarized in Table II and are shown in Fig. 9 and 10. It is seen from these figures that the mean values of Dk (dielectric constant, $\varepsilon'$) and Df (dissipation factor, or loss tangent, tan $\delta$) obtained using the VNA and (t-TRL) TDR are very close to each other, but they deviate slightly (within ~2% ) from those extracted using the algorithm [12].

2) Deviation of (t-TRL)/VNA vs. Algorithm [12]: It can be seen that both dielectric constant and loss tangent deviate from the results extracted using VNA and TDR.

The dielectric constant variation can be explained using the phase correction technique and the effects of network asymmetry that was applied to the material extraction algorithm adopted in this study. Due to the measurement inaccuracy, usually the phase gets shifted so that the phase at D.C. will not be zero. This has to be corrected by shifting the phase at each frequency point, so that the value of phase at D.C. is zero. This technique to obtain accurate phase was not considered in the. Also, the network asymmetry was not considered. Hence there is a deviation in dielectric constant. The extracted mean values are shown in Table II.

The algorithm [12] uses total alpha ($\alpha$) to extract loss tangent, whereas our material extraction procedure uses dielectric loss ($\alpha_d = \alpha - \alpha_c$) to obtain loss tangent, which yields to lower value of loss tangent.

**IV. CONCLUSION**

The material parameters were extracted using the new time domain technique called t-TRL. Time-domain measurements of all the TRL calibration patterns and test traces were conducted using a TDR. Then the frequency-domain S-
parameters were calculated using the complete FFT technique, and simultaneously applying the drift correction method. These S-parameters were used to obtain the TRL-calibrated S-parameters for the 10-inch test trace. The improved material extraction procedure was used to get the material properties from the calibrated S-parameters. The results were compared with those obtained using the VNA-TRL calibrated measurements, and also using the algorithm in [12]. The discussed herein t-TRL technique has shown to be a comparatively accurate measurement technique to extract the material properties of printed circuit boards.

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REFERENCES


